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Poster paper

Measurement and characterization of precision rotary axes at the European Synchrotron Radiation Facility

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For some beamlines, where the X-ray beam is focussed to less than 100 nm spot size, it is necessary to rotate the sample using very accurate rotary axes. The accuracy of these devices is defined in terms of radial, axial and tilt errors. At the Precision Engineering Laboratory of the ESRF, we are able to calibrate rotary stages and spindles in agreement with the ISO 230-7 and ASME B89.3.4 standards, in static mode (step by step, at given position increments) or in continuous motion. This type of measurement is possible through the use of non-contact capacitive sensors (with measuring resolution in the field of the nanometre) and reference spherical artefacts, working under controlled environmental conditions to minimize the influence of thermal instabilities. The setup includes a special granite stage with a gantry, supported by an active anti-vibration system. The presentation will illustrate the measurement principle and some examples of calibrations, including results obtained on a motorized air-bearing rotary stage for which the measured errors are about 20 nm.

1. Introduction

The present possibility of focussing X-ray beams to less than 100 nm at some ESRF beamlines demands a more precise positioning of the samples. When the sample positioning implies a full rotation, the system will include an accurate rotary axis on which calibration must be performed using measuring instrumentation and techniques that are in agreement with the metrological state of the art. Circular references (spheres or cylinders) with roundness errors limited to less than 50 nm (with calibration) and non-contact capacitive sensors (with resolution in the nanometre range) are used for this type of calibration.

Furthermore, in order to reproduce the normal working conditions of the positioner, these axes have to be measured in static mode, i.e. the progress of the rotation is done at given position increments, step by step. Working in this mode, the axes generally reveal a different behaviour to that in dynamic (continuous) mode. Consequently, the time duration of the measurement is much longer and the thermal stability is a very important aspect to consider. In any case, the

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measurement can be influenced by the vibrations and its limitation during the measurement is another important aspect to take into consideration.

An axis of rotation has six degrees of freedom (d.o.f.) of which the only desired motion is rotation. This motion is usually controlled by a driven system (motor and angle encoder). The remaining five d.o.f. should be suppressed by the guiding of the spindle or rotary stage. The combined action of the five error motions associated to these d.o.f., the three linear and the remaining two angular, is at the origin of the errors defined as radial, axial and tilt.

2. Definitions and criteria given by the standards

The definitions and measuring methods are established by ISO (ISO 230-7. Test code for machine tools. Part 7. Geometric accuracy of axes of rotation) and ANSI/ASME (ANSI/ASME B89.3.4. Axes of rotation. Methods for specifying and testing). These standards, typically oriented to the specification and test of machine tool spindles, fix two criteria for the measurements (particularly for the radial error), depending on the machining principle of the machine tool:

(i) Fixed sensitive direction: gives the error in a precise orientation (the sensor position orientation). Typically applied to the evaluation of lathe spindles where the important issue is to know the radial error in the direction of the cutting tool.

(ii) Rotating sensitive direction: allows the prediction of the error in any orientation about the stator. Typically applied to the evaluation of jig boring spindles, where the tool is rotated by the spindle.

Additionally, the errors are calculated as synchronous and asynchronous:

(iii) Synchronous error: the error that can be considered as repeatable for each turn of the axis.

(iv) Asynchronous error: part of the error that is not repeatable for each turn of the axis. Its value could include the consequence of a thermal drift.

3. Description of the measuring setup

Spindles and rotary stages used in the positioning of samples at the ESRF are measured in rotating sensitive direction. The method requires the use of two perpendicular sensors (X–Y) placed in a plane perpendicular to the axis of rotation, at a defined position along it, measuring the position of a circular reference (master sphere or cylinder) centred and fixed on the rotor of the spindle. The signals from these two sensors – which include the radial deviation of the rotation, the roundness error of the master and the residual eccentricity of the master relative to the rotor – allow the calculation of the radial error.

The axial error is measured with a third sensor oriented in the direction of the axis of rotation. If the master element is a sphere, this sensor shall be placed on its pole.

If the calibration is completed with the measurement of tilt, a double-sphere reference and a second couple of X–Y sensors are used. This setup is showed in figure 1. The results are obtained by computing the differences between the deviations measured by the sensors $X1$ and $X2$, and $Y1$ and $Y2$, respectively, and their distance along the Z-direction. This distance is the same than the distance between the two reference spheres.

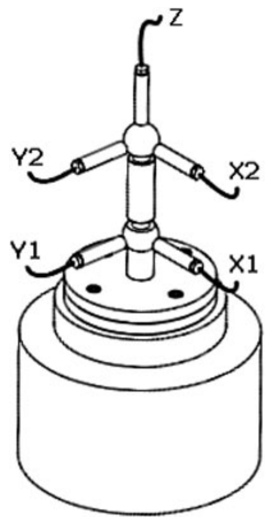

FIGURE 1. Typical setup for radial, axial and tilt measurements.

4. Error calculation

When the sensitive direction rotates with angle θ, the radial error motion is given by (figure 2)

$$\varepsilon(\theta) = \Delta X(\theta)\cos\ \theta + \Delta Y(\theta)\sin\ \theta$$

The measurements are generally performed on several bi-directional cycles of $n \times 360°$, at given angular increments (e.g. 1, 2, 5 or 10°). In our case, the data are automatically collected by a LabView® application and the calculations are performed in a spreadsheet. The error is calculated by determination of the least square circle and the minimum radial separation zone, and is represented in a polar graph.

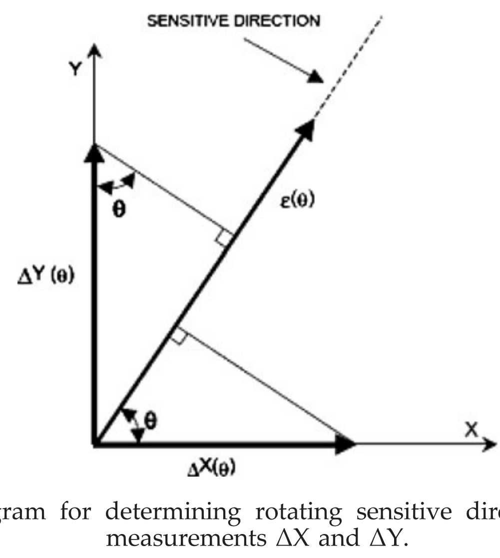

FIGURE 2. Vector diagram for determining rotating sensitive direction from orthogonal measurements ΔX and ΔY.

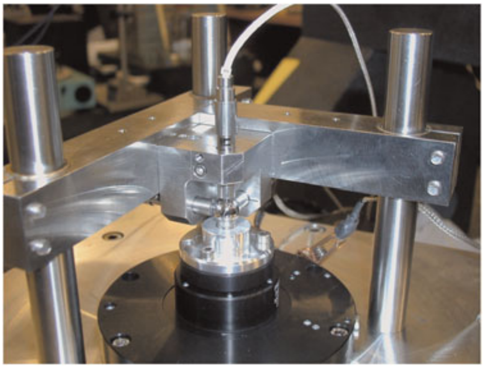

FIGURE 3. Measuring setup of the ID22 spindle.

5. Elimination of the master error

The measurement of the radial error is directly influenced by the out-of-roundness of the master. For very accurate axes of rotation, where the error could be of the same order as the master roundness, a reversal method described by Donaldson (1972) is used to separate the error of the master from the radial error motion of the axis of rotation. The method requires a second measurement (M_2) of the axis after a 180° reversion of the master relative to the rotor, and of the sensors relative to the stator.

Thus,

$$E_{\mathrm{master}} = 1/2(M_1 + M_2) \quad \text{and} \quad E_{\mathrm{spindle}} = 1/2(M_1 - M_2)$$

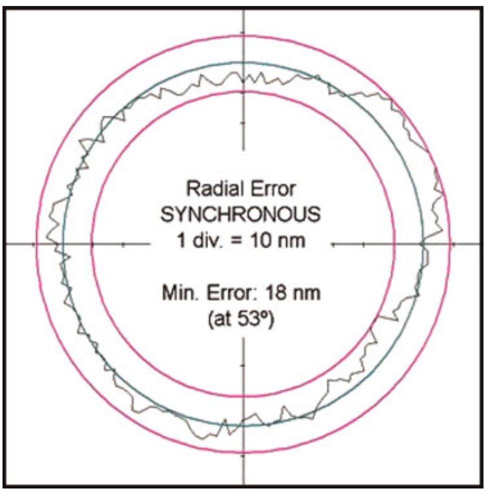

FIGURE 4. Minimum synchronous radial error corresponding to the orientation of 53°.

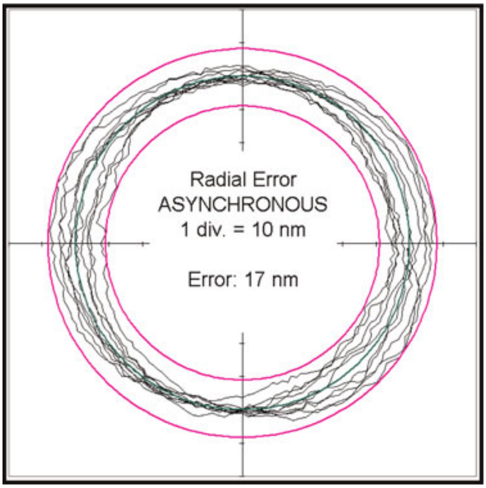

FIGURE 5. Asynchronous radial error.

6. Case study: the ID22 rotary sample positioner

The nano-analysis end station of the ESRF's ID22 beamline includes a motorized spindle whose accuracy was measured at the Precision Engineering Laboratory in January–March 2010. The system is equipped with a Professional Instruments® ISO 3R (Professional Instruments Company, http://www.airbearings.com/) air-bearing spindle, driven by a torque motor, controlled in close loop by an Etel® controller. Very accurate fittings and settings of the motor and the electronic controller parameters were crucial to minimize the influence of the magnetic forces on the radial position of the axis.

As a reference, a sphere of diameter 12.7 mm was used, placed at 23 mm from the top of the spindle. *X*–*Y*–*Z* deviations were measured by three Lion Precision® (Lion Precision, http://www.lionprecision.com/) non-contact capacitive sensors (figure 3).

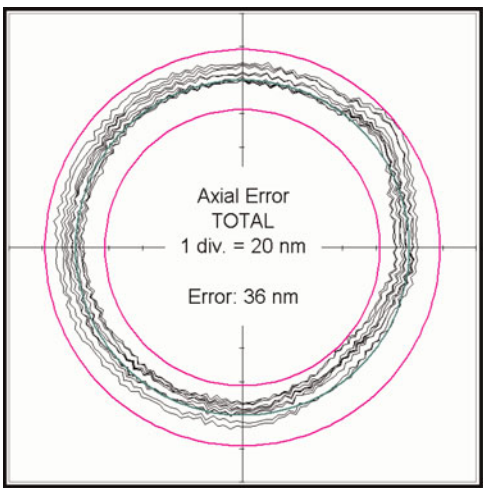

FIGURE 6. Total axial error.

The measurements were performed in bi-directional cycles of five full turns (0–1800°), every 2°. The time duration of every cycle was 150 min. The thermal stability was optimized enclosing the setup in a thermally insulated room and performing a sequence of several cycles in order to reach a stable –'in regime'– thermal condition. The evaluation was done with the measurements from the more 'stable' cycle. The separation between the roundness error of the reference sphere and the error of the spindle itself was performed using the Donaldson reversal method.

The measuring setup was installed on a granite stage lying on an active anti-vibration system.

Results obtained:

Radial error	Axial error
Synchronous:	Total: 36 nm (figure 6)
Minimum 18 nm at 53° (figure 4)	
Maximum 26 nm at 6°	
Asynchronous: 17 nm (figure 5)	

7. Conclusions

Despite all the precautions taken, it is very difficult to eliminate any thermal influence in measurements that require 150 min time to be performed and such a level of accuracy.

Thus, a thermal drift can be clearly observed in the measurement of the axial error (figure 6). The same phenomenon was observed for the asynchronous radial error (figure 5); i.e. a part of the 17 nm has to be considered a thermal drift.

Nevertheless, the degree of reproducibility of the measurements makes it possible to estimate the measurement uncertainty to less than 10 nm.

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